

AD-A200 400

FILE COPY

④

RESEARCH ON OPTIMIZATION-BASED COMPUTER-AIDED DESIGN OF CONTROL SYSTEMS

FINAL REPORT

by

Elijah Polak

for

Office of Naval Research
Contract N00014-86-K-0295

April 1, 1986 to March 31, 1988

DTIC
ELECTE
OCT 14 1988
S E D

ELECTRONICS RESEARCH LABORATORY

College of Engineering
University of California, Berkeley
94720

This document has been approved
for public release and sale in
distribution is unlimited.

88 1011 281

| REPORT DOCUMENTATION PAGE | | | | Form Approved OMB No. 0704-0188 | |
|--|-------|---|--|--|--------------------|
| 1a. REPORT SECURITY CLASSIFICATION Unclassified | | | 1b. RESTRICTIVE MARKINGS | | |
| 2a. SECURITY CLASSIFICATION AUTHORITY | | | 3. DISTRIBUTION/AVAILABILITY OF REPORT Unlimited | | |
| 2b. DECLASSIFICATION/DOWNGRADING SCHEDULE | | | | | |
| 4. PERFORMING ORGANIZATION REPORT NUMBER(S) | | | 5. MONITORING ORGANIZATION REPORT NUMBER(S) N00014-86-K-0295 | | |
| 6a. NAME OF PERFORMING ORGANIZATION Electronics Research Lab. | | 6b. OFFICE SYMBOL (If applicable) | 7a. NAME OF MONITORING ORGANIZATION Office of Naval Research | | |
| 6c. ADDRESS (City, State, and ZIP Code) University of California Berkeley, CA 94720 | | | 7b. ADDRESS (City, State, and ZIP Code) 800 N. Quincy Street Arlington, VA 22217 | | |
| 8a. NAME OF FUNDING/SPONSORING ORGANIZATION Office of Naval Research | | 8b. OFFICE SYMBOL (If applicable) | 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER | | |
| 8c. ADDRESS (City, State, and ZIP Code) 800 N. Quincy Street Arlington, VA 22217 | | | 10. SOURCE OF FUNDING NUMBERS | | |
| | | | PROGRAM ELEMENT NO. | PROJECT NO. | TASK NO. |
| | | | WORK UNIT ACCESSION NO. | | |
| 11. TITLE (Include Security Classification) Research on Optimization-Based Computer Aided Design of Control Systems | | | | | |
| 12. PERSONAL AUTHOR(S) Elijah Polak | | | | | |
| 13a. TYPE OF REPORT Final Report | | 13b. TIME COVERED FROM 4/1/86 TO 3/31/88 | | 14. DATE OF REPORT (Year, Month, Day) October 4, 1988 | |
| 15. PAGE COUNT 10 | | | | | |
| 16. SUPPLEMENTARY NOTATION | | | | | |
| 17. COSATI CODES | | | 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) | | |
| FIELD | GROUP | SUB-GROUP | | | |
| | | | | | |
| | | | | | |
| 19. ABSTRACT (Continue on reverse if necessary and identify by block number) | | | | | |
| <p>The complexity of engineering systems has increased to the extent that the interactive use of computers in their design has become more or less indispensable. Current methods of heuristic design parameter adjustment, via interactive computing, are relatively ineffective. The research covered by this report was aimed developing at a powerful, general purpose, optimization-based computer-aided engineering system design methodology. The generality of our approach is made possible by the fact that a large variety of engineering design problems are transcribable into the form of a very small number of standard, semi-infinite optimization problems, and because new system theoretic results facilitate the use of optimization in engineering design.</p> | | | | | |
| 20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS | | | 21. ABSTRACT SECURITY CLASSIFICATION | | |
| 22a. NAME OF RESPONSIBLE INDIVIDUAL | | | 22b. TELEPHONE (Include Area Code) | | 22c. OFFICE SYMBOL |

19. ABSTRACT (Continued)

The reported research can be divided into three parts: the first is was concerned with the development of semi-infinite optimization algorithms for engineering design, the second one was devoted to the development of system theoretic results which facilitate the use of optimization in control system design, and the third one was devoted to the development of an interactive software system which provides an appropriate environment for optimization-based computer-aided design.

In the process, three students completed their Ph.D. degrees, and three students are are close to completion of their doctoral research projects.

| | |
|----------------------|-------------------------------------|
| Accession For | |
| NTIS GRA&I | <input checked="" type="checkbox"/> |
| DTIC TAB | <input type="checkbox"/> |
| Unannounced | <input type="checkbox"/> |
| Justification | |
| By _____ | |
| Distribution/ | |
| Availability Codes | |
| Dist | Avail and/or Special |
| A-1 | |



The research covered by this report was aimed at developing a broad, optimization-based methodology for use in computer-aided-design of engineering systems. To this end, research was carried out in the following areas: (i) the development of a theory which can be used as a general guide in the construction of semi-infinite optimization algorithms; (ii) the development of various new semi-infinite optimization algorithms (superlinearly converging, for use when second derivatives are available, and self scaling, for use in control system design); (iii) interior penalty type algorithms which offer a possibility of improved computational efficiency; (iv) the development of techniques for formulating system stability and worst-case requirements as well-conditioned semi-infinite inequalities; (v) the exploration of the use of optimization in the design of control systems; and finally, (vi) interactive software for optimization-based control system design.

(i) Algorithm Theory.

In [7], which is a 70 page paper, we have presented our view of the mathematical foundations of nondifferentiable optimization in engineering design. The theory presented in [7] not only helps to understand existing nondifferentiable optimization algorithms, but it also provides guidelines for the development of new ones. In particular, the theory in [7] points out the possibility of the construction of self scaling algorithms. To determine what effect this might have on algorithm performance, we undertook a couple of studies of rate of convergence which were reported in [13] and

[21]. Since discretization cannot be avoided in the presence of functional inequalities, we have recently begun to develop optimal discretizations strategies to be used in the solution of control system design problems in which one shapes various closed-loop responses. We expect to present our results at the 1988 IEEE Conference on Decision and Control.

(ii) Semi-infinite Optimization Algorithms for Engineering Design.

In [3] we have developed an algorithm for the solution of optimization problems with *exclusion* constraints, which are combinatoric in nature and which arise integrated-circuit macro-cell placement problems, as a result of nonoverlap requirements. We have developed a particularly efficient formulation of the problem of placement of macro-cells in [16] and have carried out computational experiments to test it.

In [5] we have presented an exact penalty function algorithm for the solution of optimal control problems with ordinary differential equation dynamics, state, and control constraints. In [20] this algorithm was extended to apply to problems with partial differential equation dynamics and a number of internal details were made computationally more efficient. The resulting algorithm was used in computational experiments in the optimal slewing of flexible structures, which were described in [17].

In [9] we have presented an efficient generalization of Newton's method for the minimization of the maximum of a finite number of functions. At present this work is being generalized to the case minimizing the maximum of a continuum of functions.

Search direction computations consume a considerable amount of time in the course of semi-infinite optimization of engineering designs. In [23] we have proposed a new, highly efficient method for this purpose.

When linear multivariable feedback-system controllers are affinely parametrized, as is commonly done in H^∞ design, the resulting optimal design problems are convex. However, the affine parametrization can also introduce severe ill-conditioning. To overcome this effect, we have been developing domain rescaling techniques which alleviate this problem. Our first results in this area are described in [21].

(iii) Interior Penalty Algorithms for Linear Programming

Prof. C. Gonzaga, one of our collaborators, has explored the possibility of improving Karmarkar's linear programming algorithm, in a preliminary stage to the development of interior penalty function algorithms for minimax problems.

In [25] the linear programming problem is transcribed into a non-linear programming problem having as objective function Karmarkar's logarithmic potential function. The resulting problem is then solved by a master algorithm that iteratively rescales the problem and calls an internal unconstrained non-linear programming algorithm that reduces the potential function. It is shown that Karmarkar's algorithm is equivalent to this method in the special case in which the internal algorithm is reduced to a single line search. The new algorithm has the same complexity as Karmarkar's method, but the amount of computation is reduced by the fact that only one projection matrix must be calculated for each call of the internal algorithm.

In [26], the linear programming problem is transcribed into a non-linear programming problem in which Karmarkar's logarithmic potential function is minimized in the positive cone generated by the original feasible set. The resulting problem is then solved by a master algorithm that iteratively rescales the problem and calls an internal unconstrained non-linear programming algorithm. Several different procedures for the internal algorithm are proposed, giving priority either to the reduction of the potential function or of the actual cost. Karmarkar's algorithm is equivalent to the method in this paper in the special case when the internal algorithm is reduced to a single steepest descent iteration. All variants of the new algorithm have the same complexity as Karmarkar's method, but the amount of computation is reduced by the fact that only one projection matrix must be calculated for each call of the internal algorithm.

Reference [27] describes a short-step penalty function algorithm that solves linear programming problems in no more than $O(n^{0.5}L)$ iterations. The total number of arithmetic operations is bounded by $O(n^3L)$, carried on with the same precision as that in Karmarkar's algorithm. Each iteration updates a penalty multiplier and solves a Newton-Raphson iteration on the traditional logarithmic barrier function using approximated Hessian matrices. The resulting sequence follows the path of optimal solutions for the penalized functions as in a predictor-corrector homotopy algorithm.

(iv) Stability Tests and Loop-Shaping Requirement Specification.

In [8] we have presented a new stability test for linear, time invariant multivariable feedback systems, in the form of a differentiable semi-infinite inequality, and have illustrated its use in the design of Stabilizing Compensators via semi-infinite optimization.

tion. In [22], we presented a version of this test which can be used in the design of *finite dimensional* controllers for Infinite dimensional feedback-systems via semi-Infinite optimization. In [18] we presented a coherent approach to semi-infinite optimization-based design of both open-loop and closed-loop control systems for flexible structures. In particular, we showed that frequency domain design of closed loop systems, using our stability test, produces finite-dimensional controllers without spill-over effects. In [11, 12] and [14], we have explored various aspects the design of linear multivariable feedback-systems via constrained semi-infinite optimization in " H^∞ Spaces". These included a study of expansions of the controller in a series, development of expressions for both time- and frequency-domain loop shaping, as well as an exploration of the numerical properties of the ensuing *convex* optimal design problem.

(v) Novel Control Schemes and Computational Procedures.

In [6] we have presented a novel adaptive control scheme for ARMA plants. The scheme is based on sequential plant uncertainty identification and control system redesign using worst case design by semi-infinite optimization. In [1] we have presented a particularly efficient diagonalization technique for the computation of sensitivity functions of linear, time-invariant multivariable systems, both open- and closed-loop. In [25] we have presented a computational complexity reduction technique for use in control system design when the plant models incorporate both structured and unstructured uncertainty. Experiments testing the effectiveness of this technique were described in [2].

(vi) Software.

A version of DELIGHT.MIMO: which is an interactive system for optimization-based multivariable control system design has been completed and described in [15]. Recently a user's manual has been prepared for this system as part of an M.S. project.

We are currently implementing a second generation DELIGHT system which is computationally more efficient, and is significantly easier to maintain than the existing system. An important feature of this system is the X Window System based user interface, which significantly extends the rudimentary interface of the existing system. The new system emphasizes control system design and the interface allows the user to interactively enter design parameters and configurations, and to interpret system performance.

(vii) Survey Papers.

We have written and presented a number of survey papers to assist the engineering community in making effective use of semi-infinite optimization in design, see [4, 7, 10, 19].

REFERENCES

- [1] T. L. Wu, R. G. Becker and E. Polak, "A Diagonalization Technique for the Computation of Sensitivity Functions of Linear Time Invariant
IEEE Trans. on Automatic Control, Vol. AC-31 No. 12, pp. 1141-1143, 1986.
- [2] D. M. Stimler and E. Polak, "Nondifferentiable Optimization in Worst Case Control Systems Design: a Computational Example", *Proc. IEEE Control Systems Society 3rd Symposium on CACSD*, Arlington, Va., September 24-26, 1986.
- [3] D. Q. Mayne and E. Polak "Algorithms for Optimization Problems with Exclusion Constraints", *JOTA*, Vol. 51, No. 3, pp. 453-474, 1986

- [4] E. Polak and D. Q. Mayne, "Design of Multivariable Control Systems via Semi-Infinite Optimization", *Systems and Control Encyclopaedia*, M. G. Singh, editor, Pergamon Press, N.Y. 1987.
- [5] D. Q. Mayne and E. Polak "An Exact Penalty Function Algorithm for Control Problems with State and Control Constraints", *IEEE Trans. on Control*, Vol. AC-32, No. 5, pp. 380-388, 1987.
- [6] E. Polak, S. Salcudean and D. Q. Mayne, "Adaptive Control of ARMA Plants Using Worst Case Design by Semi-Infinite Optimization, *IEEE Trans. on Automatic Control*, Vol. AC-32, No. 5, pp. 388-397, 1987.
- [7] E. Polak, "On the Mathematical Foundations of Nondifferentiable Optimization in Engineering Design", *SIAM Review*, pp. 21-91, March 1987.
- [8] E. Polak and S. Wu, "On the Design of Stabilizing Compensators via Semi-Infinite Optimization", *University of California, Berkeley, Electronics Research Laboratory Memo No. M86/102*, Oct. 24, 1986. *IEEE Trans. on Automatic Control*, in press.
- [9] E. Polak, D. Q. Mayne and J. Higgins, "A Superlinearly Convergent Algorithm for Min-Max Problems", *University of California, Berkeley, Electronics Research Laboratory Memo No. M86/103*, Nov. 15, 1986.
- [10] E. Polak, "A Perspective on Control System Design by Means of Semi-Infinite Optimization Algorithms", *Proc. IFIP Working Conference on Optimization Techniques*. Santiago, Chile, Aug. 1984. Springer Verlag. 1987
- [11] E. Polak and S. E. Salcudean, "On The Design of Linear Multivariable Feedback Systems via Constrained Nondifferentiable Optimization in H^∞ Spaces", *IEEE Trans on Automatic Control*, in press.
- [12] E. Polak and S. E. Salcudean, "Algorithms for Optimal Feedback Design", *Proc. International Symposium on the Mathematical Theory of Networks and Systems (MTNS/87)*, Phoenix, Arizona, June 15-19, 1987.
- [13] E. Polak, C. Gonzaga and J. Wiest, "Linear Convergence of Semi-Infinite Programming Algorithms", 11th Triennial IFORS Conference on Operations Research, Buenos Aires, Argentina, August 10-14, 1987.
- [14] Septimiu E. Salcudean, "Algorithms for Optimal Design of Feedback Compensators", Ph.D. Thesis, *University of California, Berkeley*, December 1987.
- [15] Tzyh-Lih Wu, "DELIGHT.MIMO: An Interactive System for Optimization-Based Multivariable Control System Design", Ph.D. Thesis, *University of California, Berkeley*, December 1987.
- [16] S. Daijavad, E. Polak, and R-S Tsay, "A Combined Deterministic and Random Optimization Algorithm for the Placement of Macro-Cells", *University of California, Berkeley, Electronics Research Laboratory Memo No. UCB/ERL M87/86*, Nov. 20, 1987. *Proc. MCNC International Workshop on Placement and Routing*, Research Triangle Park, NC, May 10-13, 1988.
- [17] T. E. Baker and E. Polak, "Computational Experiments in the Optimal Slewing of Flexible Structures", *University of California, Berkeley, Electronics Research*

Laboratory Memo No. UCB/ERL M87/72, Sept. 1, 1987.

- [18] E. Polak, T. E. Baker, T-L. Wu and Y-P. Harn "Optimization-Based Design of Control Systems for Flexible Structures", *Proc. 4-th Annual NASA SCOLE Workshop*, Colorado Springs, December 1987.
- [19] E. Polak, "Minimax Algorithms for Structural Optimization", *Proc. IUTAM Symposium on Structural Optimization*, Melbourne, Australia, Feb. 9 - 13, 1988.
- [20] T. Baker, "Algorithms for Optimal Control of Systems Described by partial and Ordinary Differential Equations", Ph.D. Thesis, *University of California, Berkeley*, January 1988.
- [21] E. Polak and J. W. Wiest, "Domain Rescaling Techniques for the Solution of Affinely Parametrized Nondifferentiable Optimal Design Problems", To be presented at 1988 IEEE CDC.
- [22] Y-P. Harn and E. Polak, "On the Design of Finite Dimensional Controllers for Infinite Dimensional Feedback-Systems via Semi-Infinite Optimization", To be presented at 1988 IEEE CDC. *University of California, Berkeley, Electronics Research Laboratory Memo No. UCB/ERL M88/17* 26 February 1988.
- [23] J. E. Higgins and E. Polak, "Minimizing Pseudo-Convex Functions on Convex Compact Sets", *University of California, Berkeley, Electronics Research Laboratory Memo No. UCB/ERL M88/22*, March 1988.
- [24] E. Polak and D. M. Stimler, "Majorization: a Computational Complexity Reduction Technique in Control System Design", *IEEE Trans. on Automatic Contr.*, in press.
- [25] C. Gonzaga, "A Conical Projection Algorithm for Linear Programming," *University of California, Berkeley, Electronics Research Laboratory Memo No. UCB/ERL M85/61*, July 25, 1985.
- [26] C. Gonzaga, "An Algorithm for Solving Linear Programming Problems in $O(n^3L)$ Operations," *University of California, Berkeley, Electronics Research Laboratory Memo No. UCB/ERL M87/10*, March 5, 1987.
- [27] C. Gonzaga, "Conical Projection Algorithms for Linear Programming," *University of California, Berkeley, Electronics Research Laboratory Memo No. UCB/ERL M87/11*, March 5, 1987.